Regional Stratification and Shear of the Various Streams Feeding the Philippine Straits

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LONG-TERM GOALS

The Analysis of in situ and satellite data with model output to investigate the stratification and shear of the Philippine seas at sub-meso to meso-scales to regional scales, so as to understand their relationship to the larger scale ocean and monsoon forcing. This work contributes to the "Characterization and Modeling of Archipelago Strait Dynamics" DRI [PhilEx] goal: to enhance our understanding of the oceanographic processes and features arising in and around straits, and improve our capability to predict the inherent spatial and temporal variability of these regions using models and advanced data assimilation techniques.

OBJECTIVES

To resolve the circulation and mixing within the Philippine Archipelago and neighboring seas [South China Sea, Sulu Sea and boundary with the open Pacific Ocean]. Features and processes of particular interest are those associated with the interaction of the mean and tidal currents with the strong seasonal forcing at regional and smaller scales, including the effects of the complex topography characteristic, passage constrictions and topographic sills of the Archipelago; the interaction of the interior seas of the Philippine Archipelago [Mindanao and Sibuyan Seas] with the larger scale dynamics; dense 'ventilating' overflow into isolated deep basins; the response of the circulation to highly textures wind stress curl patterns induced by the Archipelago configuration.

APPROACH

The stratification and circulation is revealed through an array of CTD/Lowered ADCP stations, as well as underway data [notably the hull mounted ADCP, SST/SSS and surface chlorophyll] collected during the field phase of PhilEx: Exploratory Cruise, June 2007; Regional IOP-08, January 2008; and Regional IOP-09, March 2009, as well as during the Joint Cruise of November/December 2007. These data are integrated with other observational data, including satellite sensing, moored instrumentation and model output, as needed to meet the DRI objectives. I collaborate with other DRI observationalists: Amy Ffield, Earth and Space Research: LADCP; Pierre Flament, University of Hawaii at Manoa: High frequency radio; Craig Lee, University of Washington: towed vehicles and Gliders; James Girton: EM profilers; Janet Sprintall, Scripps Institution of Oceanography: ADCP moorings; and Cesar Villanoy and Laura David, both at the Institute of Marine Research at the

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University of the Philippines: biochemical data. The model collaboration is accomplished via H. Hurlburt, J. Metzger, W. Han, J. Levin, B. Zhang, H. Arango, J. Doyle, P. May, J. Pullen and P. Lermusiaux.

WORK COMPLETED

Contributions to the following 3 physical oceanographic regional themes were made in fy 10, and reported in the Results section:

1. Archipelago interior [stratification, velocity/transport] response to remote and local forcing.
2. Identification of the dominant physical and dynamical balances that characterize the flow & mixing at different locations and scales within the Philippine Archipelago.
3. Evaluation of models simulation the observed characteristics.

RESULTS

The specific advances in the fy10 period are:

General Oceanography of the Philippine Seas.

[A] A PhilEx issue of The Oceanography Society *Oceanography* is being prepared for March 2011 publication. A.L.Gordon and C. Villanoy are Guest Editiors. As of 30 September there are 8 articles under review. The Gordon and Villanoy Introduction to the PhilEx special issue "The Oceanography of the Philippine Archipelago":

Stretching some 2800 miles from Australia to Asia is a most impressive feature: an array of islands, straits and seas of varied sizes and depths, incorporating the Indonesian and Philippine domains. The regional mix of land and ocean, at the nexus of ENSO and Asian monsoon, where waters of the Pacific western boundary currents weave their way into the Indian Ocean, is exposed to a monsoon climate and strong tidal activity, making the "Mega"Archipelago of the southeast Asian Seas a challenge to observe and to model. To enhance our understanding of ocean dynamics within Archipelago configurations, as required to improve our capability to predict oceanic spatial and temporal variability, a program within the Philippine region (Figure 1), involving a suite of in situ and remote observational methods with global and regional model components, Philippines Experiment (PhilEx) Department Research Initiative (DRI) was sponsored by the Office of Naval Research. PhilEx involved US and Philippine research from numerous institutions.

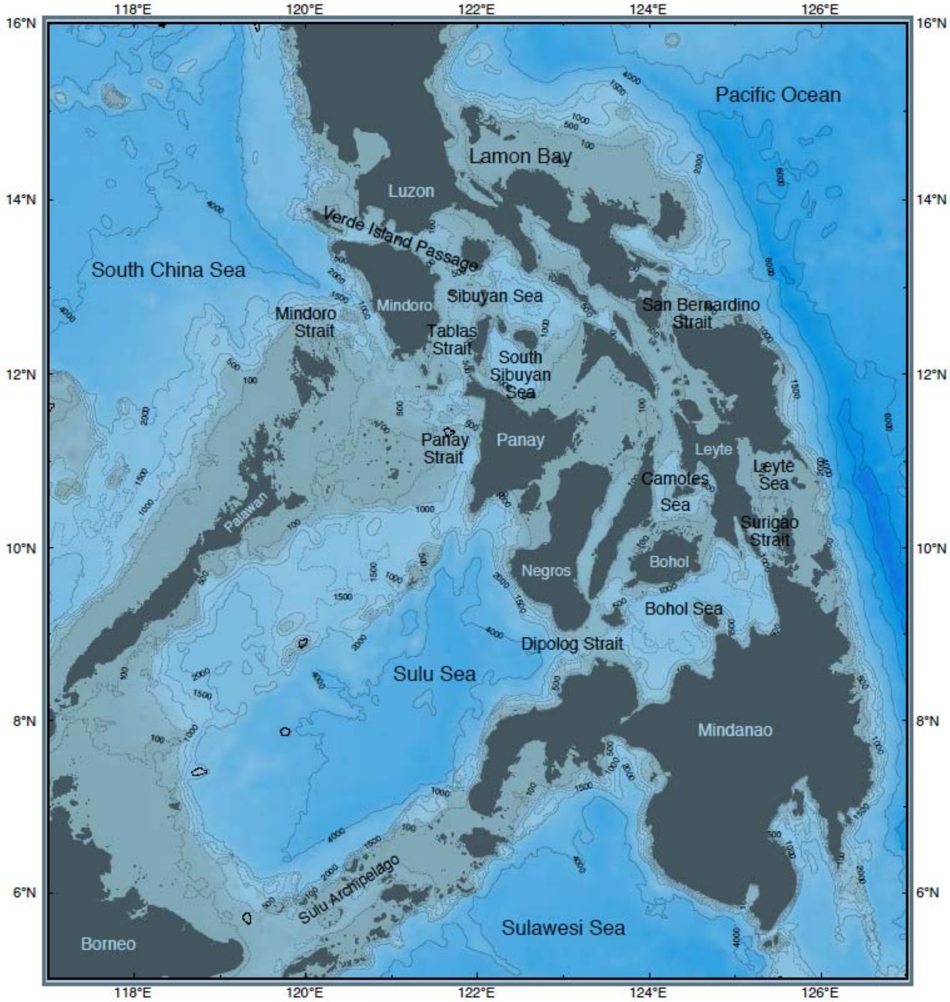

Figure 1: Bathymetry of the seas and straits of the Philippine archipelago from Smith and Sandwell, 1997, http://topex.ucsd.edu/marine_topo/

PhilEx investigators posed a series of specific research questions: How does the archipelago stratification and circulation pattern respond to remote and local forcing? What are the dominant physical and dynamical balances that characterize the flow and mixing at different locations and scales within the Philippine Archipelago? How well do models simulate the observed characteristics? What are effective paradigms for representing Archipelagos dynamics? During cruise planning it became apparent that not only did the complexities of the flow within the network of straits and seas require high resolution observations, but also that a basic exploratory element was needed to better define the regional waters of the Philippine Seas.

There were 4 major PhilEx expeditions aboard the R/V Melville: June/July 2007; November/December 2007; January/February 2008; and February/March 2009, whose snapshot views provided by CTD/LADCP, underway surface data, including hull ADCP, towed vehicles, linked together with an array of timeseries observations from moorings and sensors aboard untethered drifters, gliders and profilers. Land based high frequency radio provided a high spatial resolution of the surface currents within Panay Strait. Remote observations of sea surface temperature, ocean color, sea level from earth orbiting satellite complete the observational PhilEx menu, all of which are related to the output of

varied models, as HYCOM, ROMS, COAMPS. Observations from ongoing programs provided information on the larger scale setting for the PhilEx program.

PhilEx uncovered many fascinating features of the horizontal and overturning circulation patterns across a broad range of spatial and temporal scales within the Philippine region that are presented in this Oceanography collection.

[B] Gordon, Sprintall, Ffield, "Regional Oceanography of the Philippine Archipelago" *Oceanography,* Under review for March 2011 PhilEx issue

The objective of this paper is to provide an introduction to the regional setting to place in context the information presented in the collection of studies presented in the PhilEx issue of *Oceanography*. We use data from the regional PhilEx hydrographic cruises and moored time series measurements (Figure 2) to describe the flow pattern and water mass distribution within the Philippine archipelago.

Summary statement: Confined by the intricate configuration of the Philippine Archipelago, forced by the monsoonal climate and tides, responding to the remote forcing from the open Pacific and adjacent seas of Southeast Asia, the internal Philippine seas present a challenging environment to both observe and model. The Philippine Experiment (PhilEx) observations reported here, provide a view of the regional oceanography for specific periods. Interaction with the western Pacific occurs by way of the shallow San Bernardino and Surigao Straits. More significant interaction occurs via the Mindoro and Panay Straits with the South China Sea, which is connected to the open Pacific through the Luzon Strait. The Mindoro/Panay throughflow reaches into the Sulu Sea and adjacent Bohol and Sibuyan Seas, via the Verde Island Passage, Tablas and Dipolog Straits. The deep isolated basins are ventilated by flow over confining topographic sills that displace upward the older residence water made more buoyant by vertical mixing, which is then exported to surrounding seas to close the overturning circulation circuit.

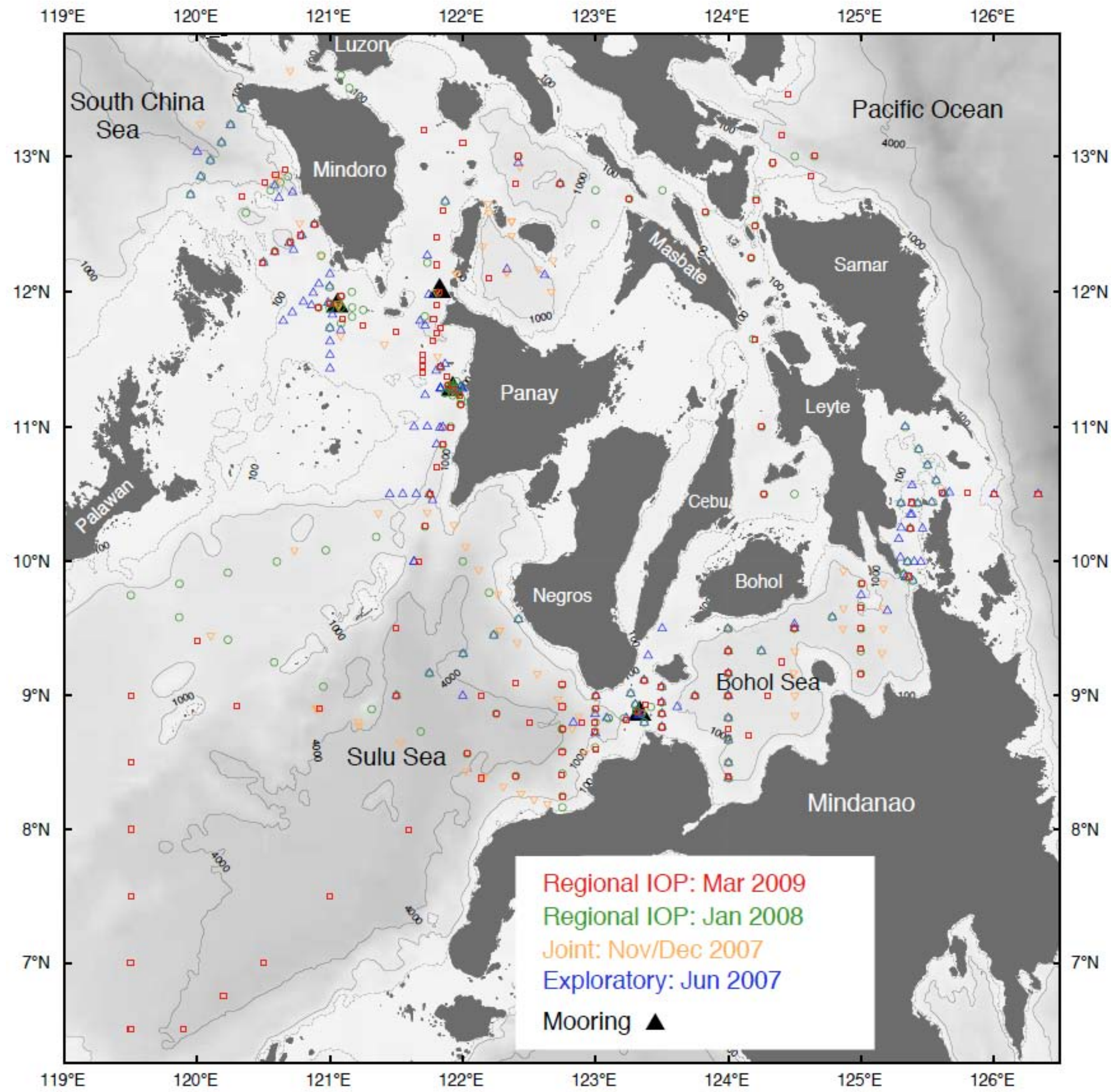

Figure 2. Conductivity, temperature, depth and dissolved oxygen and lowered Acoustical Doppler Current Profiler (CTD-O_2/LADCP) stations obtained by the four PhilEx cruises. The position of the PhilEx moorings are shown.

Stratification of Philippine waters (Figure 3): With descent into the water column the warm low salinity surface water above the top of the thermocline at 50-70 m, rapidly gives way to cooler, saltier water at 200 m (Figure 3, upper panels). The potential temperature (θ°C) drops by ~10°C over only 100 m, from 70 to 170 m, coinciding with an intense pycnocline in which density increases by nearly 3 sigma-0 units, from 22.5 to 25.2. In early summer the SST of June 2007 was about 2° warmer than in January 2008 or March 2009. The SSS range between cruises amounts to 1.0 psu, with the lowest SSS in January 2008. The highest SSS is in June 2007, a consequence of the normal dry season compounded by the drier conditions of an El Niño. The lowest SSS was observed in January 2008 (as well as during the Joint Cruise of late 2007), a consequence of the phasing out of the previous wet season, whereas in March 2009, nearly two more months into the dry season, SSS was slightly more elevated. The lowest SSS (<33.4) are observed in the Bohol Sea and the South China Sea entrance to Mindoro Strait during the winter regional cruises, perhaps a consequence of the delayed river runoff

from their respective larger neighboring landmasses of Mindanao and Luzon. The Sibuyan and Camotes Seas SSS are between 33.4 and 33.6. The seasonal influence determined by comparing the salinity differences between the PhilEx cruises is found to reach to about 130 m, into the mid-thermocline.

The relatively warm thermocline data (Figure 3) are from the western Pacific adjacent to the San Bernardino and Surigao Straits. In the salinity profiles these stations display the pronounced salinity maximum (s-max) in the 75-250 m, 16° to 28°C interval that mark the North Pacific Subtropical Water. While the shallow San Bernardino and Surigao Straits block s-max water, North Pacific Subtropical Water has access to the South China Sea via Luzon Strait. However at the South China Sea entrance to Mindoro Strait, the pronounced s-max core in the 20° to 28°C range is greatly attenuated with only a weak s-max near 28°C as observed in the June 2007 cruise, or a T/S flexure near 25°C in both of the regional 2008 and 2009 cruises, and a deeper s-max near 16°C. The processes within the South China Sea that attenuate the North Pacific subtropical s-max are beyond the scope of this paper.

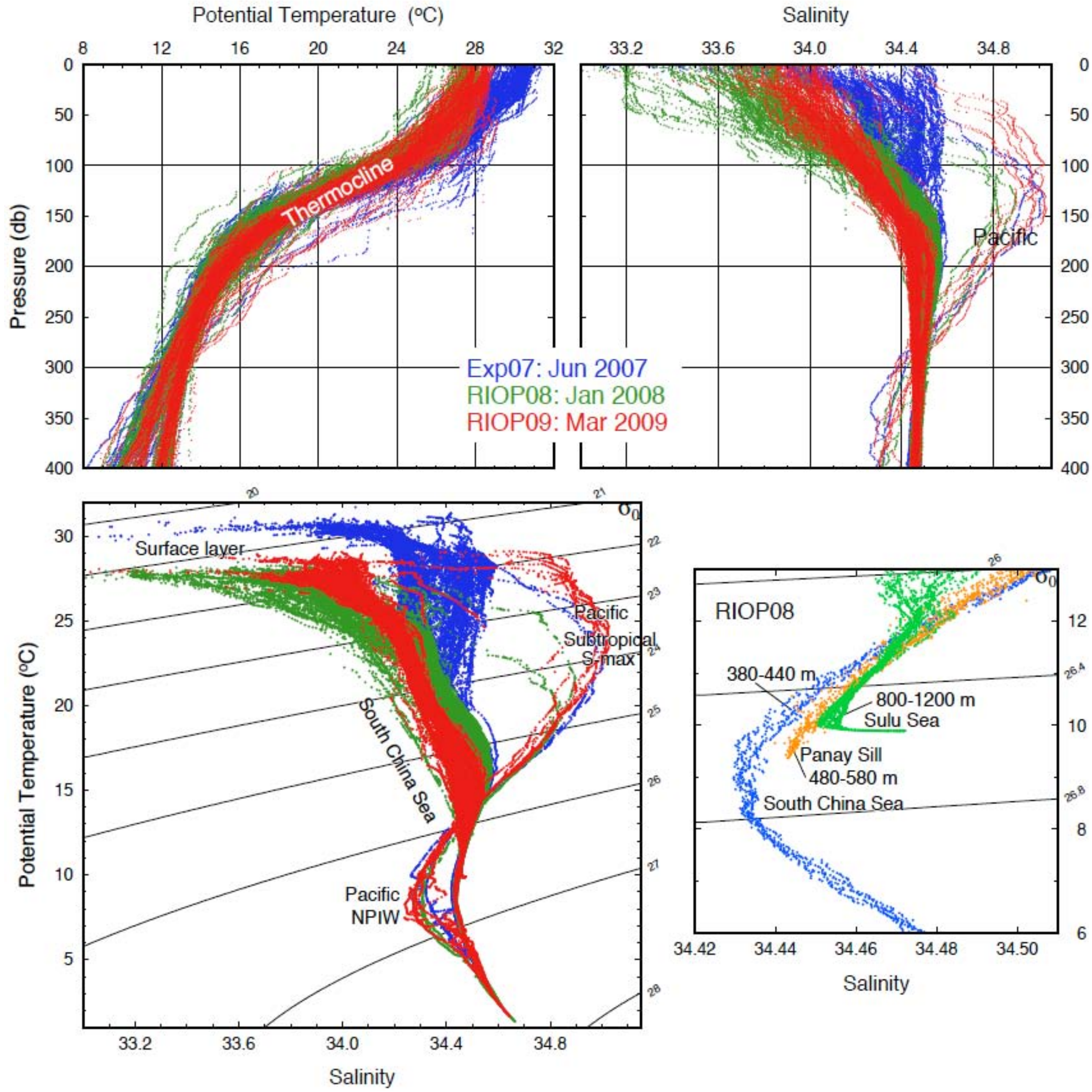

Figure 3 Temperature, salinity and oxygen from the CTD obtained on PhilEx exploratory cruise (June 2007); regional cruise 2008 (January 2008); and regional cruise 2009 (March 2009).Upper panels: Potential temperature and salinity profiles with pressure (depth) for the upper 400 m for the three PhilEx cruises. Lower panels: Potential temperature and salinity scatter plot. The lower left shows a blow-up of the 6° to 13°C strata. Potential temperature and oxygen profiles below 100 m for the deep basins of the Philippine archipelago.

A salinity minimum (s-min) is observed from 350 to 600 m in the western Pacific stations, marking North Pacific Intermediate Water, which also has access to the South China Sea via Luzon Strait. An attenuated but still visible s-min near 10°C is observed in Mindoro and Panay Straits. It is this water that provides the overflow into the Sulu Sea (Tessler et al., 2010). The θ/S structure (Figure 3, lower left panel) further brings out the stratification features of the Philippine waters, particularly the 'gap' between the western North Pacific saline subtropical water and fresher thermocline water of the

Philippine waters, as well as the attenuated North Pacific Intermediate Water s-min in the Mindoro and Panay Straits. There are two CTD stations (Figure 3) in the southern Sulu Sea from March 2009 that show relatively warm, salty water between 125 and 150 m which mark the trough of the Solitons observed in that area.

The Philippine seas are composed of numerous deep basins isolated from one-another by topographic barriers (Figure 1). There is the open deep Pacific Ocean to the east; there are the relatively large seas to the west of the Philippines: the Sulu Sea, South China Sea and Sulawesi Sea; and there are the smaller interior seas, most notably the Bohol Sea and the Sibuyan Sea, and the still smaller Visayan and Camotes Seas (Figure 1). Below roughly 500 m these seas have marked differences in θ (and S) and oxygen values (Figure 4) from each other and from the source water column of the open western North Pacific. These marked property differences are a product of topographic barriers.

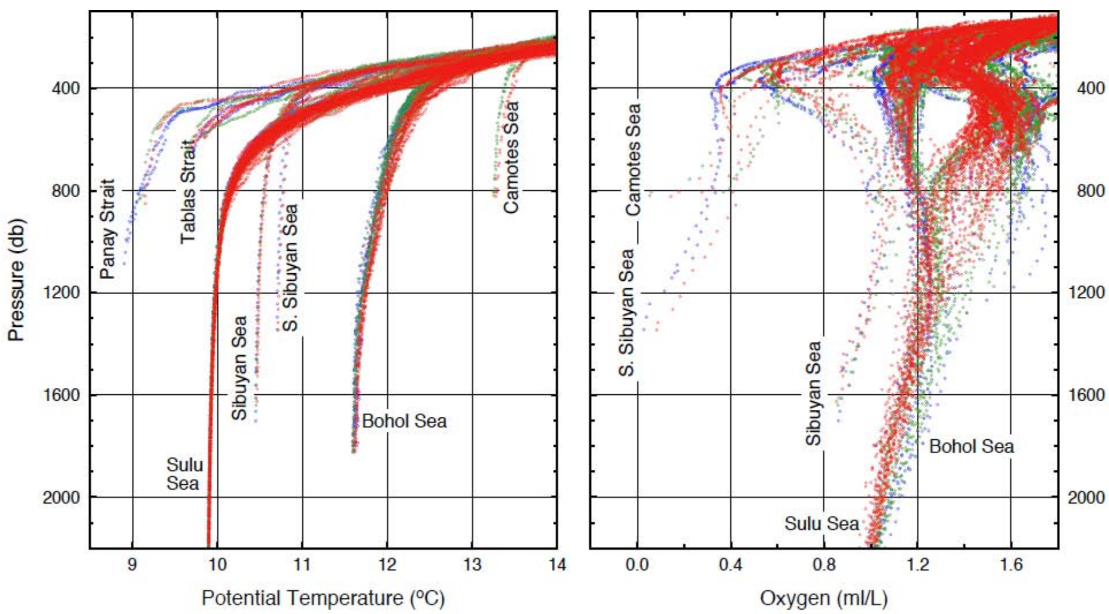

Figure 4 Potential temperature and oxygen profiles below 100 m for the deep basins of the Philippine archipelago. The wide range of temperature and oxygen result from the varied depths of the confining topographic sills for each isolated basin and on the oxygen consumption rates relative to the vertical eddy mixing environment within the isolated deep basins.

The isolated deep basins are ventilated by sill spillover, often quite vigorous (Tessler et al, 2010) from surrounding seas that descend to the depths replacing resident water made less dense by vertical mixing. The residence water is lifted upward by denser overflow water, and is subsequently exported to the surrounding seas to close the overturning circulation cell. As these waters are reduced in oxygen by the rain of organic material from the sea surface, their spreading can be traced as an oxygen minimum. For example the Bohol Sea oxygen minimum near 12°C is observed near 300 m throughout the Sulu Sea with traces in Panay Strait.

The interaction of the Bohol Sea with the Sulu Sea to the west via the Dipolog Strait and Pacific Ocean to the east via the Surigao Strait is turning out to be a most fascinating topics. The 47 km wide (as

measured between the 100 m isobaths) Dipolog Strait, with a sill depth of 504 m, separates the Bohol Sea from the Sulu Sea and is the deepest connection of the Bohol Sea to surrounding seas. The Dipolog Strait is of prime importance in ventilating the subsurface layers of the Bohol Sea. The eastern end of the Bohol Sea is connected to the Pacific Ocean across the broad, shallow Leyte Sea through a 58 m deep Surigao Strait, through which there appears to be a small net flow of surface water into the eastern Bohol Sea. As described above Surigao inflow streams across the northern Bohol Sea to be exported into the Sulu Sea through Dipolog Strait. The northern Bohol Sea has connectivity to San Bernardino Strait by way of a 330 km long narrow channel that runs through the Camotes Sea to enter the Bohol Sea both to the east and west of Bohol Island. This channel has a 18-meter deep constriction to the northeast of Bohol Island and a 3 km wide though deep (280 m) channel to the northwest of Bohol Island. The PhilEx observations indicate that the throughflow (based on ADCP and CTD data) in these channels is negligible, but this channel may be an effective way to deliver river runoff from the islands of the central Philippines, and reduces the SSS of the northern Bohol Sea.

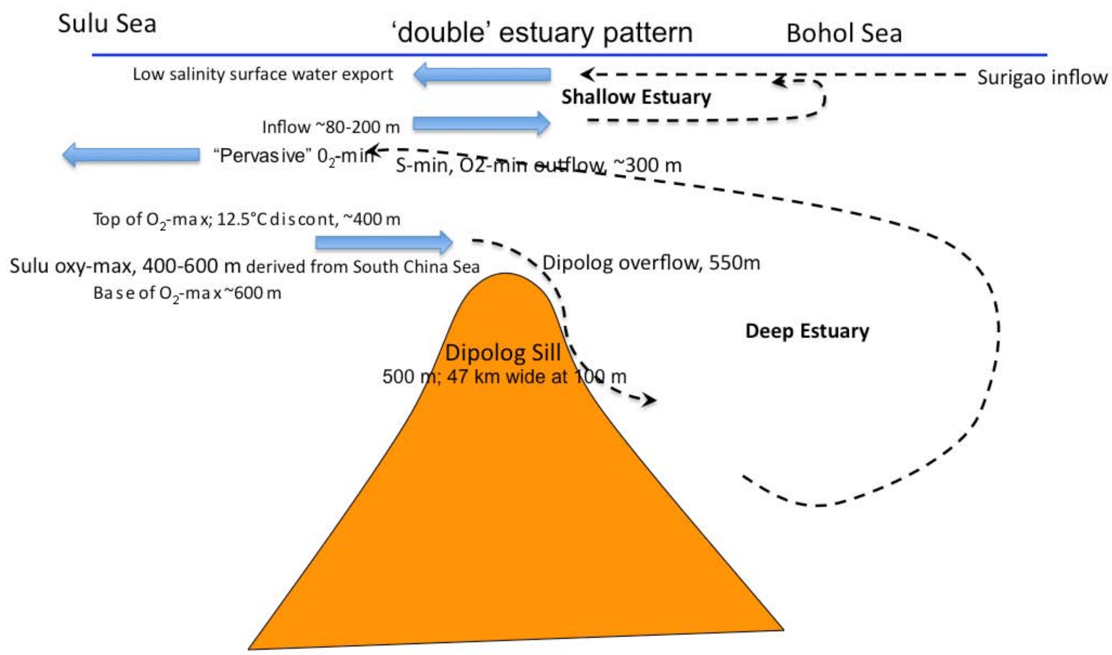

Figure 5 Schematic representation of the water exchange between the Bohol Sea and the Sulu Sea through Dipolog Strait. The depiction is based on the CTD-O_2/LADCP data from the PhilEx cruises.

The LADCP profiles reveal the highly layered circulation profile within the Dipolog Strait with two layers of inflow into the Bohol Sea and two outflow layers. The layers which exhibit export into the Sulu Sea are the surface water of the upper 50 m the other centered at 300 m. One can envision a double estuary overturning circulation within the Bohol Sea (Figure 5). The shallow estuary circulation is composed of surface water outflow to the Sulu Sea, compensated with upwelling by entrainment of thermocline inflow waters into the Bohol Sea, bolstered by the Surigao throughflow. The deeper estuary overturning circulation is controlled by dense water overflow to the depths of the Bohol Sea within the lower 50-100 m of the Dipolog Strait, with export in the 300-350 m interval towards the Sulu Sea derived from the upward displaced resident water. This water is low in oxygen (~1.3 ml/l)

and is the likely source of a low oxygen core within the Sulu Sea within that depth interval. Estimates from the LADCP and mooring time series suggest that the deep overturning circulation amounts to ~0.2 Sv. The westward transport in the upper limb of the shallow cell, as estimated from the PhilEx cruises LADCP data across Dipolog Strait, may amount to ~0.5 Sv, part of which is drawn from the Surigao Strait. As the LADCP average for the lower limb is ~0.2 Sv, the Surigao Strait throughflow is probably around 0.3 Sv, assuming the Bohol Sea river inflow is negligible.

The Mindoro and Panay Straits connect the Sulu Sea with the South China Sea. These straits exhibit much variability in depth and width. A schematic of the Mindoro/Panay throughflow (Figure 6) provides a sense of the mean throughflow conditions. However, wind induced energetic eddies as observed in January-February 2008 induce much intraseasonal activity in this region that can obscure the mean, longer-term conditions. In the upper 150 m there is net flow towards the South China Sea. Eddies are generated as this flow encounters Apo Reef. At and below 150 m the flow is towards the Sulu Sea. Above ~500 m this water spreads at a similar depth into the Sulu Sea, marking a s-max near 300 m and an oxygen maximum near 500 m, traces of which enter into the Bohol Sea. Spill over topographic sills occurs into the Semirara Sea (the isolated 1300 m deep basin south of the Semirara Islands) and over the Panay sill to depths of 1200 m in the Sulu Sea.

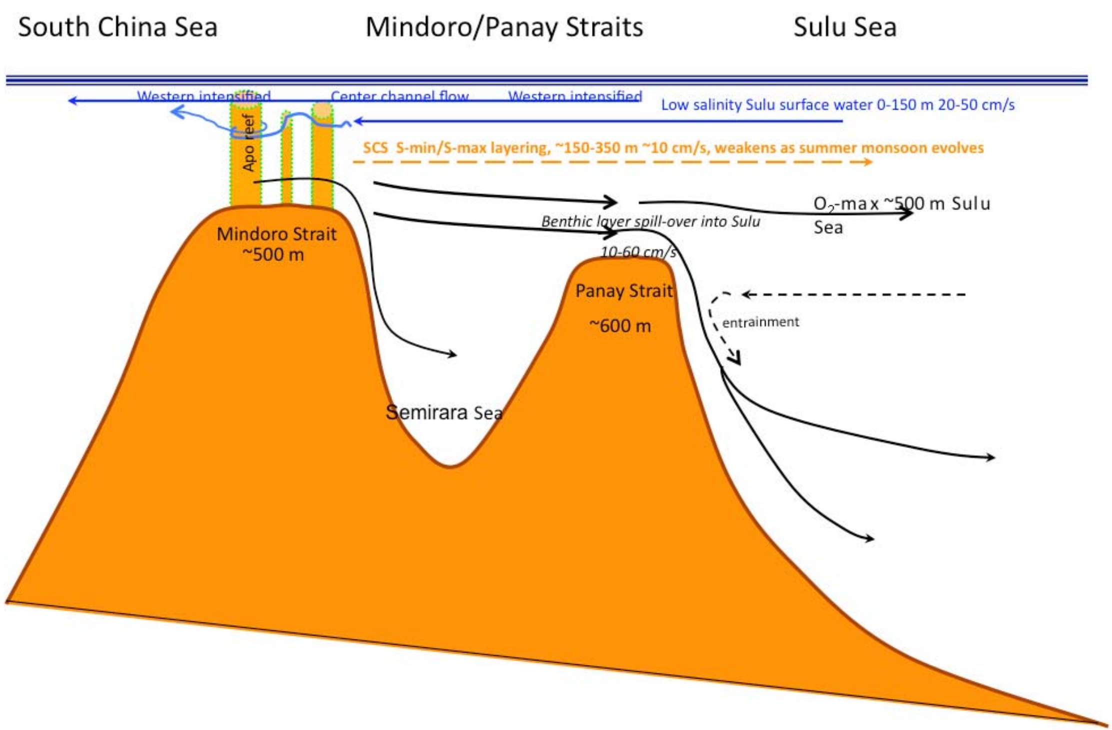

Figure 6 Schematic representation of the water exchange between the South China Sea and the Sulu Sea through Mindoro and Panay Straits. The depiction is based on the CTD-O_2/LADCP data from the PhilEx regional 2008 and 2009 cruises.

Specific Regional Studies

[A] Bohol Sea Circulation and Ventilation

§ Cabrera, Villanoy, David, Gordon, "Barrier Layer Control of Entrainment and Upwelling in the Bohol Sea, Philippines" *Oceanography*, Under review for March 2011 PhilEx issue.

Abstract: Bohol Sea is a relatively unstudied marginal sea found in the southern part of the Philippines. Hydrographic data from PHILEX cruises show a complex 3-dimensional circulation that is composed of two overturning cells, a circulation that is referred to as “double-estuarine type”. A consequence of this type of circulation is entrainment and eddy-upwelling of cold-nutrient rich waters that theoretically should promote blooms of phytoplankton. Evidence from ocean color support entrainment in the eastern basin and eddy formation in the southwestern basin but the cyclonic Iligan eddy was found not to conform to the paradigm of eddy upwelling. Although upwelling was evident through doming isothermals, the signal was suppressed by the presence of a thick barrier layer, particularly during cruises in December 2007 and January 2008, a known La Niña period. Long-term trends of chlorophyll data followed trends in rainfall and ENSO 3.4 index, with elevated (reduced) chlorophyll during dry El Nino years (wet La Nina years). The barrier layer, by promoting stability of stratification and preventing vertical transport of nutrients, is thus a mechanism by which ENSO influences phytoplankton biomass in the Bohol Sea

[B] Sulu Sea Circulation and Ventilation:

§ Martin, J.P. and A.L. Gordon. "Exploratory Observations of Physical Processes in the upper Sulu Sea". submitted to AGU Fall 2010 meetings:

Abstract: The Sulu Sea extends roughly 600 km in all directions, is up to 5 km deep, and is connected to the Pacific Ocean, but only via surrounding seas through several straits of varying width and depth. The Dipolog Strait between the Philippine islands of Mindanao and Negros connects the Sulu to the Bohol Sea. Straits between the islands of Panay, Palawan and Borneo connect the Sulu to the South China Sea. Straits between Borneo and Mindanao connect the Sulu to the Sulawesi Sea. External interactions with the Sulu Sea include strait currents, monsoon wind stress, tides and internal waves propagating into the sea from the perimeter. Mooring observations indicate large intraseasonal signals in currents through the Dipolog Strait and the Cuyo East Passage, west of Panay. Known impacts on the Sulu thus have timescales ranging from a day to a year. Currents through the boundary straits reverse direction with depth and so have a complex interaction with the Sulu Sea. To explore physical processes in the Sulu Sea, four in situ surveys were conducted between June 2007 and March 2009 during the Philippines Straits Dynamics Experiment (PhilEx). Observations collected include current from hull-mounted Doppler sonar and temperature, salinity, dissolved oxygen and fluorescence from station casts and underway surface measurements. Horizontal shear dominates the surface current pattern. The shear’s horizontal scales are small compared to the Sulu Sea’s dimensions. The surface water also has significant density fronts at scales similar to the horizontal shear. This horizontal structure is described by viewing observed properties on maps and as a function of along-track position. Horizontal structure is quantified by computing basic statistics along-track and through spectral and wavelet analysis. A topic investigated is the relative role of boundary strait current variability and wind forcing in generating the observed horizontal shear and density fronts. When currents directed into the Sulu are stronger, more energy could be available for eddies in the sea and these eddies could have sizes related to strait dimensions. Sulu Sea water is traced to sources in boundary straits. One example is relatively warm and fresh surface water which appears to come from

the Balabac Strait between Palawan and Borneo. A broader horizontal picture of the Sulu Sea is established by using remote sensing and numerical model output.

§ Sulu Sea ventilation from the South China Sea, via Panay Strait (Tessler, Z., A.L.Gordon, L.Pratt, J. Sprintall, Panay Sill Overflow Dynamics. J. Phys. Oceanogr., *in press*).

Abstract: Observations of stratification and currents between June 2007 and March 2009 reveal a strong overflow between 400 m to 570 m depth from the Panay Strait into the Sulu Sea. The overflow water is derived from approximately 400 m deep in the South China Sea. Temporal mean velocity is greater than 0.75 m/s at 50 m above the 570 m Panay Sill. Empirical orthogonal function analysis of a mooring time series shows the flow is dominated by the bottom overflow current with little seasonal variance. The overflow does not descend below 1250 m in the Sulu Sea, but rather settles above high-salinity deep water derived from the Sulawesi Sea. The mean observed overflow transport at the sill is 0.32 $x10^6$ m^3 s^{-1}. The observed transport was used to calculate a bulk diapycnal diffusivity of 4.4 x 10^{-4} m^2s^{-1} within the Sulu Sea slab (575 m to 1250 m) ventilated from Panay Strait. Analysis of Froude number variation across the sill shows the flow is hydraulically controlled. A suitable hydraulic control model shows overflow transport equivalent to the observed overflow. Thorpe-scale estimates show turbulent dissipation rates up to 5 x 10^{-7} W kg^{-1} just downstream of the supercritical to subcritical flow transition, suggesting a hydraulic jump downstream of the sill.

§ Gordon, Tessler, Villanoy, Duel Overflows into the Deep Sulu Sea. [likely submission to GRL before the end of 2010].

Summary: The Sulu Sea lies within a 5 km deep basin, isolated from the neighboring ocean below 570 m. The deep Sulu Sea potential temperature is nearly isothermal; with a slight minimum at 2800 m. Below 1250 m is a marked salinity increase with depth. A single overflow source would induce a homogeneous volume within the deep Sulu Sea. The deep ventilation source is attributed to South China Sea water overflowing a 570 m sill in Panay Strait. The Panay overflow amounts to 0.32 Sv of 9.67°C and 34.44 salinity water. The Sulu bottom water is 9.9°C and 34.474. The Sulu T/S profile indicates that Panay overflow floods the Sulu Sea from 570 to 1250 m, with a residence time of 11 years, and is unlikely to serve as the source for the deeper Sulu Sea. We propose that the deep and bottom Sulu Sea ventilation is derived from overflow from the Sulawesi Sea, via the Sibutu Passage sill of 340 m. There a mix of Sulawesi water from 200 to 800 m is required. We hypothesis that this overflow and mixing is achieved in ‘bursts’ in the tidal active Sibutu Passage (which is source of Sulu Sea Solitons). Oxygen concentrations indicate that the Sulawesi overflow is 0.16 Sv, the a residence time of the Sulu Sea bottom water of 65 years. Thus the Sulu Sea has the distinction of being ventilated from two separate sources. It is conceivable that the ratio of the northern and southern sources vary with ENSO and long time scales.

§ Zachary D Tessler, Arnold L Gordon "ENSO Modulated Variability of the Panay Sill Overflow" presented at the AGU OS in Portland OR in Feb 2010 ***Oceanography of Archipelagos*** Conveners: Gordon, Arnold L., Lamont-Doherty Earth Observatory/ Columbia; Pullen, Julie, Stevens Institute of Technology.

Summary: Archived hydrographic data from the South China Sea suggest ENSO related variability in the strength of the Panay Sill Overflow into the Sulu Sea. The overflow is drawn from the Western Pacific, passes through the South China Sea, and into the Mindoro and Panay Straits. CTD and bottom-

moored observations at Panay Sill show the flow to be relatively well described by a 1.5-layer hydraulic control model. Using hydrographic stations at Panay Sill and in the South China Sea, we map Panay Sill Overflow water to approximately 400 m in the South China Sea, and the overlying water at the sill to approximately 250 m. Flow dynamics at Panay Sill are strongly dependent on vertical density structure, suggesting upstream changes in temperature are important. A monthly subsurface temperature database based principally on the World Ocean Database 2005 is used to estimate past variability in the overflow based on changes in the upstream water column temperature structure. We find a correlation between the NINO 3.4 index and the temperature difference between 250 and 400 m in the South China Sea, with the La Nina phase of ENSO correlating with increased Panay Sill transport. Our results suggest that the Panay Sill Overflow and associated ventilation of the Sulu Sea varies by approximately 20% between ENSO phases.

[C] Mindoro and Panary Straits:
Pullen, Gordon, Sprintall, Lee, Alford, Doyle, May, "Winds, Eddies and Flow through Straits" *Oceanography*, Under review for March 2011 PhilEx issue.

Abstract: A reversal of the mean flow through the Philippines' Mindoro Strait occurred in early February 2008. The flow was southward through the strait during late January and northward during most of February. The flow reversal coincided with the period between two intensive observing cruises (IOP08-1 and IOP08-2) sponsored by Office of Naval Research (ONR) as part of the Philippine Straits Experiment (PhilEx). Employing high resolution models of the ocean and atmosphere along with *in situ* ocean and air measurements, we detail the regional and local features that influenced this flow reversal. High-resolution air/sea modeling simulations captured the flow reversal and agreed with measured currents from two moorings in the vicinity of Mindoro Strait. A short (24-27 January) easterly monsoon surge and a longer (9-16 February) northerly surge were represented in the model as well as in QuikSCAT and underway wind data taken during IOP08-2. Mesoscale oceanic dipole eddies off Mindoro and Luzon (Pullen et al., 2008) were formed/enhanced and subsequently detached by these wind events. The cyclonic eddy associated with the easterly surge was opportunistically sampled during the IOP08-1 cruise and the modeled eddy characteristics were verified using *in situ* shipboard data. The presence of the cyclonic eddy near Mindoro Strait favored a geostrophic flow southward through the strait. This dominant flow was interrupted by a strong and sustained wind-driven (by the northerly surge) flow reversal in early February when the cyclonic eddy was absent. Enhanced upper ocean stratification in winter 2008 due to anomalously high precipitation served to isolate the near-surface circulation in the observations.

IMPACT/APPLICATIONS

The PhilEx cruises provide information for addressing the PhilEx objectives, by resolving the stratification and circulation patterns inder varied forcing conditions, within the complex topography of the Phillipine Seas. The resultant numerical model, honed by observations, and the enhanced understanding of the oceanography of the Philippine waters to be produced by the PhilEx program will have a multitude of applications in managing marine resources and the marine environment of the Philippines and other archipeligos, as well as for issues of marine safety and prediction of marine pollution dispersion.

TRANSITIONS

None

RELATED PROJECTS

None

REFERENCES

Cabrera, Villanoy, David, Gordon, "Barrier Layer Control of Entrainment and Upwelling in the Bohol Sea, Philippines" *Oceanography*, Under review for March 2011 PhilEx issue.

Gordon, Sprintall, Ffield, "Regional Oceanography of the Philippine Archipelago" *Oceanography*, Under review for March 2011 PhilEx issue

Pullen, Gordon, Sprintall, Lee, Alford, Doyle, May, "Winds, Eddies and Flow through Straits" *Oceanography*, Under review for March 2011 PhilEx issue.

Rypina, I., L.J. Pratt, J. Pullen, J. Levin, and A.L. Gordon, 2010: Chaotic advection in an archipelago, J. Phys. Oceanogr. September issue, *in press.*

Smith, W. H. F., and D. T. Sandwell, Global seafloor topography from satellite altimetry and ship depth soundings, Science, v. 277, p. 1957-1962, 26 Sept., 1997, http://topex.ucsd.edu/marine_topo/

Tessler, Z., A.L.Gordon, L.Pratt, J. Sprintall, 2010: Panay Sill Overflow Dynamics. J. Phys. Oceanogr., *in press*.

PUBLICATIONS

Rypina, I., L.J. Pratt, J. Pullen, J. Levin, and A.L. Gordon, 2010: Chaotic advection in an archipelago, J. Phys. Oceanogr. September issue, *in press.*

Tessler, Z., A.L.Gordon, L.Pratt, J. Sprintall, 2010: Panay Sill Overflow Dynamics. J. Phys. Oceanogr., *in press*.

PATENTS

None